DEVICES AND CONTROL STRATEGIES FOR *AD HOC* OPTICAL COMMUNICATIONS NETWORKS

Final Report

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1.FOREWARD

The research under this project has been aimed at proving the potential value of key elements (both hardware and operational concepts) that we plan to develop in initiating an ambitious program of research to develop a radical new technology for high-bandwidth, stealthy communication over free-space optical links.

The results of the project have been several prototype systems which integrate optical components (a MEMS-based spatial light moudlator (SLM) integrated with a retroreflector to produce an inexpensive and lightweight device which is capable of reliably modulating a laser beam probe and reflecting it to its place of origin), a state-of-the-art, low-power RF device (MOTE), and an autonomous robot vehicle on which these components can be mounted. Continuing research is aimed at developing the underlying control principles for operating a system which integrates the above components in a way that will support future research on mobile *ad hoc* optical communications networks.

2. LIST OF APPENDICES (If any)

None.

3. STATEMENT OF THE PROBLEM STUDIED

This report describes a nine-month research project which has been aimed at designing, fabricating, and testing a novel system which can be used for low-power, inexpensive, and stealthy free-space optical communications. The work has combined microelectromechanical systems (MEMS) deformable mirrors with commercial corner-cube retroreflectors to produce active modulated retroreflecting (MR) devices. An important novel element in these autonomous MR device nodes is that they rely on a a remote node's laser beam for power, thus requiring almost no local power to communicate stealthily over long distances. The basic concept is depicted in Figure 5.

For the work reported here, a primary motivation was to build a functional prototype sensor network of modulated retroreflectors that combine long range with low power and low cost. In prior work at BU, a modulated retroreflector was designed and built. The pilot system used existing

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6. AUTHOR(S)
John Baillieul and Thomas Bifano

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Boston University, Aerospace and Mechanical Engineering, 110 Cummington Street, Boston, MA 02215

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13. ABSTRACT (Maximum 200 words)

The research under this project has been aimed at proving the potential value of key elements (both hardware and operational concepts) that we plan to develop in initiating an ambitious program of research to develop a radical new technology for high-bandwidth, stealthy communication over free-space optical links.

The results of the project have been several prototype systems which integrate optical components (a MEMS-based spatial light modulator (SLM) integrated with a retroreflector to produce an inexpensive and lightweight device which is capable of reliably modulating a laser beam probe and reflecting it to its place of origin), a state-of-the-art, low-power RF device (MOTE), and an autonomous robot vehicle on which these components can be mounted. Continuing research is aimed at developing the underlying control principles for operating a system which integrates the above components in a way that will support future research on mobile ad hoc optical communications networks.

14. SUBJECT TERMS
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Enclosure 1

MEMS DMs, which were developed at Boston University (BU) over the past several years for use in adaptive optics applications.

Figure 1 illustrates the general features of a BU device. The modulated retroreflector application requires only a single actuation channel, with one-bit of resolution. To achieve simple modulation, 70 actuators were connected in parallel to a binary high-voltage square wave driver and the other 70 actuators were connected in parallel to ground. The MEMS-DM is incorporated into a modulating retroreflector device by mounting it into a high-quality retroreflecting corner cube as illustrated in Figure 1.

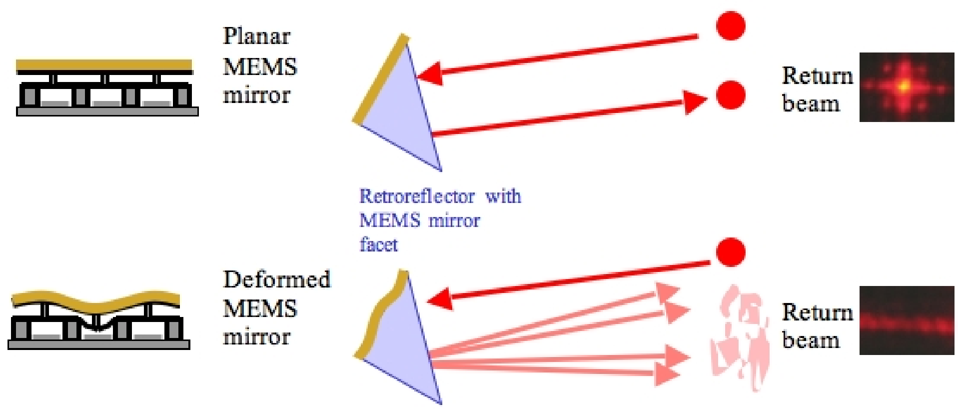

Figure 1: : Modulated retroreflector concept. A micromachined deformable mirror serves as one facet of a corner cube retroreflector. The MEMS device has the characteristic that it can be made to act as a normal plane mirror, or it can be deformed, using fast, low-power electrostatic actuation. When coupled to the retroreflector, the device maximizes light intensity returned toward the source when the MEMS mirror is planar, and minimizes it when the MEMS mirror is deformed. As a result, the return beam intensity is modulated by a ratio of up to 1000:1. A receiver at the source node can interpret the modulated return beam through a variety of time based communication protocols (frequency modulation, amplitude modulation, pulse width modulation etc.)

A. Prior Work Modulated Retroreflectors.

Retroreflectors are comprised of three mutually orthogonal reflective surfaces that come together at an interior corner. Because of this geometry, they are often called “corner-cubes.” This simple geometry has an important optical effect: light rays incident upon the retroreflector over a relatively wide cone of incidence angles (typically $\sim 60^{\circ}$) will re-emerge from the retroreflector in the opposite direction, parallel to the incident beam. This geometric property can be exploited with particular advantage in optical systems requiring a round-trip transmission path between two nodes without the extra requirement for pointing and tracking at both ends.

Perhaps the most well known use of retroreflectors as remote sensors was in NASA’s Apollo Mission. The Apollo 11 lunar module — carrying the first astronaut crew to the moon — contained as one of its few scientific instruments a Laser Ranging Retroreflector (LRRR), consisting of 100 corner-cube prisms in a 10×10 array. Interrogated by a pulsed laser beacon from earth, this device and two devices delivered later in Apollo missions 14 and 15 have been used to track, with centimeter-scale precision, the distance between the earth and the moon. The LRRR is the only Apollo experiment that is still returning data from the Moon [2].

In prior work on modulated retroreflection, two notable efforts include work by researchers at the University of California at Berkeley (UCB) for an all-MEMS chip based device [3,4] and at the US Naval Research Laboratory (NRL) for a retroreflector with an aperture controlled by an active electronic shutter [5,6].

The UCB MEMS corner cube retroreflector was fabricated using SOI (silicon on isolator) micromachining technology. A quadruplet retroreflector was manually micro-assembled from three different micromachined parts, produced using a combination of lithographic patterning, deep reactive ion etching, HF etching, and thick photoresist patterning processes [2]. Retroreflector modulation was achieved by actuating the bottom layer of the device, while two vertical mirror surfaces remained fixed. The required electrostatic actuation voltage was only 5V. Though not demonstrated in the prototype, it is conceivable that later versions would be suitable for automated micro-assembly using tools adapted from the telecommunications optical fiber industry. Nevertheless, this manufacturing and assembly task poses a substantial challenge. The device's measured resonance frequency was ~7kHz, though its under-damped actuation limited prototype performance to ~1kHz. This device holds considerable promise for the category of network systems dubbed "dust motes," in which low-level, short-range communication among millimeter scale chips is a primary objective. However, the inverse relationship between optical aperture and beam divergence limits this millimeter-scale device's use in networks with appreciable distances between nodes.

The NRL work demonstrated a much higher bandwidth device in a modulated retroreflector communication system that used multiple quantum well (MQW) electro-optical shutters to pass or block light incident on conventional optical retroreflectors. This coupled system allowed modulated retroreflection without moving parts. Also this modulator is exceptionally fast, allowing communication at rates of tens of megahertz. The MQW modulators used in this program consisted of about 100 very thin (10 nm) layers of semiconductor materials, (e.g. GaAs, AlGaAs, and InGaAs) epitaxially deposited sequentially on a semiconductor wafer. When driven by an external modulation circuit, the optical absorbance of the shutter changes over a narrow range of wavelengths. MQW shutters were shown to operate at low power (~50mW). These modulated retroreflectors were designed specifically for remote video transmission from unmanned autonomous vehicles, an application in which they have demonstrated remarkable performance. Limitations of the MQW approach include the inherently high cost of MQW devices, the relatively low optical switching contrast ratio (~2.5:1), and the narrow optical bandwidth over which a particular MQW device will operate as a shutter [5].

4. SUMMARY OF IMPORTANT RESULTS

A. Modulated Retroreflectors.

In recent work conducted on this project, a series of modulators were fabricated though a MEMS foundry. These modulators were comprised of a silicon membrane mirror supported by continuous, slender, parallel rib attachments to an underlying substrate. On the substrate, a single electrode beneath the entire membrane was used to provide a driving electrostatic force that could corrugate the mirror. The on-axis reflection from the surface was considerably attenuated by this corrugation.

The electromechanical performance of the device was affected by its rib geometry, and three different rib spacings were used in the prototype design . The devices were packaged and tested. It was found that strong modulation could be achieved at relatively input low voltages (20V), which is an important factor for overall power conservation of the system. Figure 2 shows a portion of the

mask layout used to design these devices on the left, and a photograph of a packaged set of four modulators on the right.

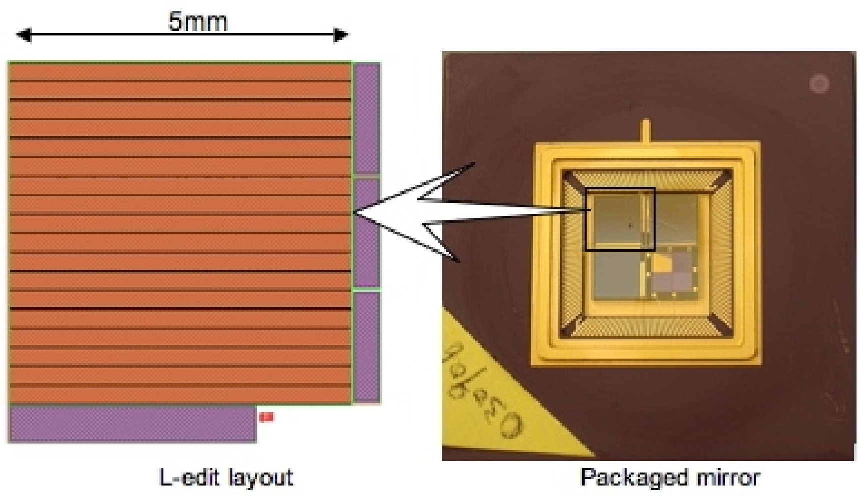

Figure 2: A foundry process was used to develop chip-based silicon MEMS modulators employing electrostatic actuation. The devices modulate by deflecting the nominally flat membrane mirror between rows of anchor attachment ribs.

The devices were characterized for their dynamic performance by driving them electrostatically with an input square wave while measuring the surface defelction midway between two ribs using a laser doppler vibrometer. For all three ribs span designs, the resonant frequenct of the device was found to be greater than 100kHz, as illustrate in Figure 3.
To further test the devices, some were packaged by bonding them directly to one facet of a gold-coated pyrex retroreflector. In this configuration, the devices could be tested as part of an actual modulated retroreflector communication link. This work builds on prior research that resulted in the development of an interrogating laser and a set of pules-width modulated driver electronics. Testing of the combined system is underway currently, with two students actively engaged in experimental laser communication at 1550nm wavelength over 100m path lengths. A photograph of the modulated retroreflector prototype is shown in Figure 4.

B. Design and Fabrication of an Optical Mote Communications Device

While the modulated retroreflector is of interest in its own right, one of the major goals of this research project has been to develop a system which could be used to evaluate these optical devices in applications involving mobility. The Intelligent Mechatronics Lab at Boston University has considerable experience with MICA2 Motes interfaced with small robots as depicted in Figure 6. These Motes are outgrowths of research at U.C Berkeley on low power radio-enabled sensors, and they have been used fairly extensively at Boston University in research on mobile sensor networks.

To make the interface depicted in Figure 5 work, it was necessary to be able to pass a signal from the mote to the modulated retroreflector. This was accomplished using the Atmel128 micro controller on the Mote, which was programed using NesC and assembly language to generate a PWM signal. The connection of the MICA2 to amplifier of the DM was via the 51-pin expansion connector on the Mote which can be seen in the figure. In this connector, there are three PWM

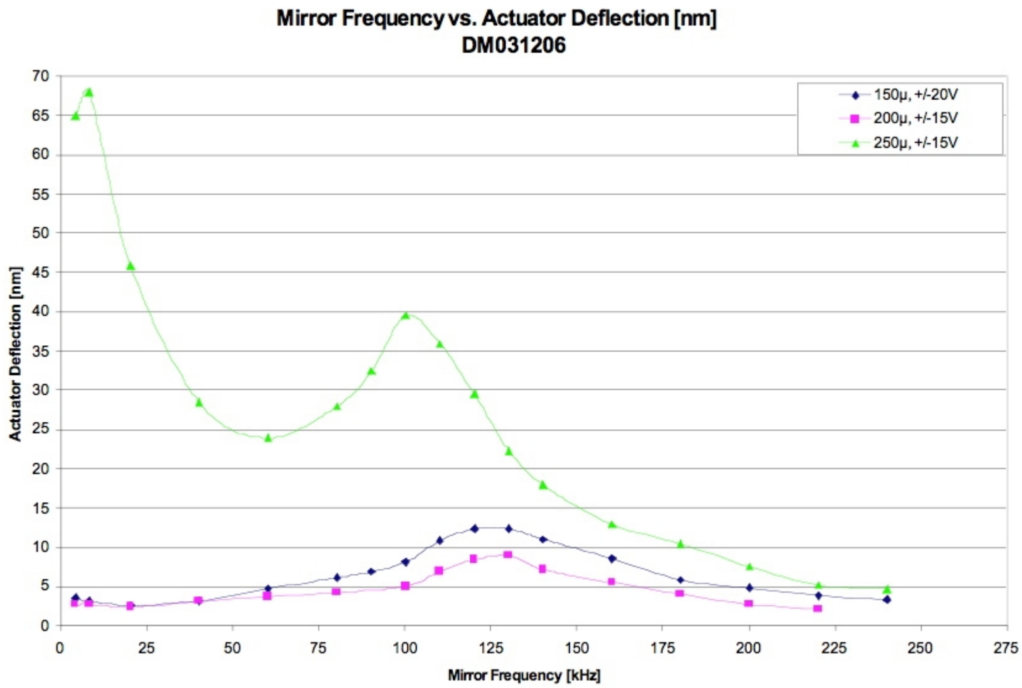

Figure 3: Mirror maximum deflection in response to an applied voltage measured as a funcrion of drive frequency for three different modulators having inter-rib spacing of 150, 200, and 250 micrometers.

output pins, and for this project it was decided to connect the 16 bit PWM to provide the control signal to the DM. Because the Mote-native TinyOS does not easily permit a PWM signal to be initiated, the project needed to rely on assembly language to carry out this function.

C. Position Control to Establish and Maintain Optical Communications Links - position servoing based on bit-error rate feedback. Free-space optical communication links involving devices of the type described in the preceding section mounted on robot vehicles such as those depicted in Figure **??** present a number of challenges related to establishing and maintaining the optical links. Ongoing research is aimed at addressing problems in

1. *cooperative search strategies* by which beam transmitters and receivers will locate each other to establish optical links;
2. *control stragtegies* for maintaining optical links between vehicles which are in motion (and which may be in motion relative to each other); and
3. the use of the *quality of the link* as a figure of merit on which to base real-time motion planning. Specifically, research is needed to understand the use of measured bit-error rates as a feedback signal for motion servoing.

While complete solutions of these problems are beyond he scope of the project reported here, we are now working on some prototype problems to address problems 1 and 2 in using the robot mounted devises depicted in Figure **??** in our Small Robot Testbed. The research team has considerable experience using Mote-born sensors to guide motions of the robots, and our current research is aimed at extending our previously developed sensor-based control laws in order to use bit-error

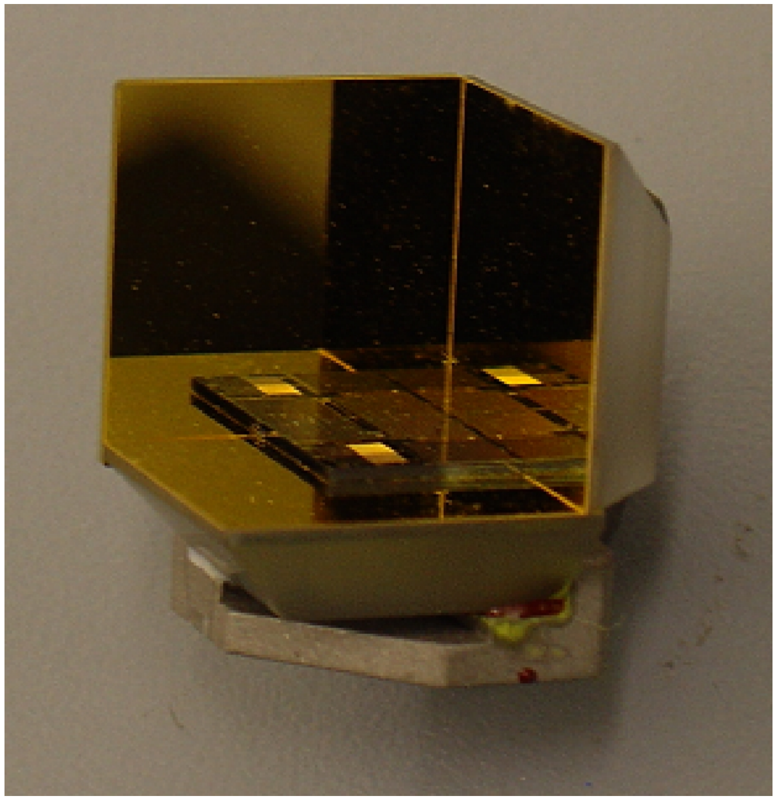

Figure 4: The newly developed MEMS modulator is packaged along one facet of a commercial glass retroreflector.

rate as a feedback signal. These control laws are designed to follow level curves of sensor values. Our own experience as well as a growing body of published research (See [1] and the references cited therein.) indicates that this is a feasible approach to controlling the robot motions in order to maintain the optical communications link.

D. Future Research Directions

Future research will be aimed at planning group motions which combine the objectives of moving two or more vehicle between prescribed positions while optimally supporting optical communications by means of the systems under discussion. One idea along these lines involves motion planning which is referenced to the measured direction of the communications beam. As described above, the MR sensor assemblies on each robot vehicle will be steerable and able to align themselves so as to maximize the quality of the optical signal (minimizing the bit-error rate of the received signals). In minimizing this bit error rate, the sensor mechanism will approximately align itself with the direction of the beam, and using information about the direction of the beam, vehicles can plan motions which whose directions are resolved into components aligned with and orthogonal to the beam direction. This decomposition of motion vectors will be useful in applications where moving robot vehicles need to maintain reliable optical communication links throughout the motions. To maintain maximally reliable channel operation, each vehicle can transmit its planned motion increments with respect to these beam-referenced directions.

Important Special Considerations in the Control of Optical Communications Links between Mobile Agents. *Ad hoc* optical communications technologies present a number of

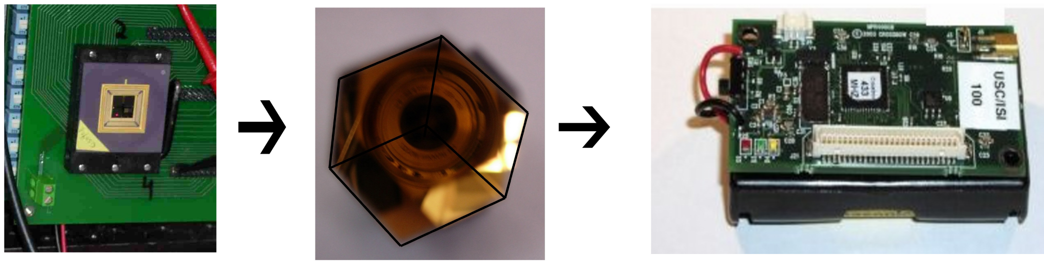

Figure 5: The basic elements of the retroreflecting optical communications device are depicted here. A 140 element DM has been installed on one face of a high-quality retroreflecting cube. For continuing research in a network of mobile communications nodes, the retroreflecting cube is subsequently mounted on a MICA2 Mote, with the DM amplifier circuit connected via the 51-pin Hirose connector depicted here.

unique challenges.

1. *Great versus small separation distances.* Because of the highly directional nature of laser-mediated optical communication links, a major challenge in a fieldable system is the maintenance of the link at both short and long ranges. For large separation between optical transmitters and receivers, interference and atmospheric attenuation and distortion may become serious issues. For small separation, on the other hand, the time constants in steering the communications devices on a vehicle may become the major challenge.

2. *Tracking signal quality—position control based on error rates.* There is growing interest in controlling autonomous vehicles to follow lines of constant sensor readings. (See [1] and [2].).For the mobile optical MOTE system described above, work continues on the use of detected bit-error rates as a measure of the quality of an optical communication link. Special probe signals with known content are being tested for use in orienting the modulated retroreflector (Figure 7.) to establish an optimum quality optical communication link for the proposed probe based communication application.

3. *Changing levels of optical adversity.* In the early prototype systems of Figure 5, we have begun to study the problem of steering the communications devices to compensate for intermittently obstructed views which arise as a consequence of the vehicle moving through an area with natural and artificial objects that obstruct line-of-sight communications links. Atmospheric turbulence, smoke, fog, etc. may also degrade the performance of optical communications systems. It is precisely under such adverse conditions that we believe it will be useful to evaluate the use of bit-error rate to evaluate performance and to provide the necessary feedback to steer the MR sensors described above.

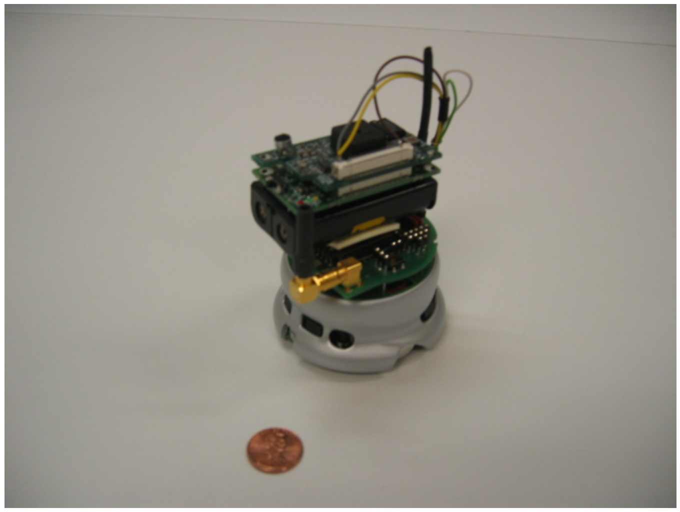

Figure 6: The Mote-retroreflector device depicted in Figure 5 will be mounted on one of our Khepera robots and evaluated in the Intelligent Mechatronics Lab's Small Robot Testbed. The robot with a MICA2 Mote mounted is seen here next to a U.S. penny.

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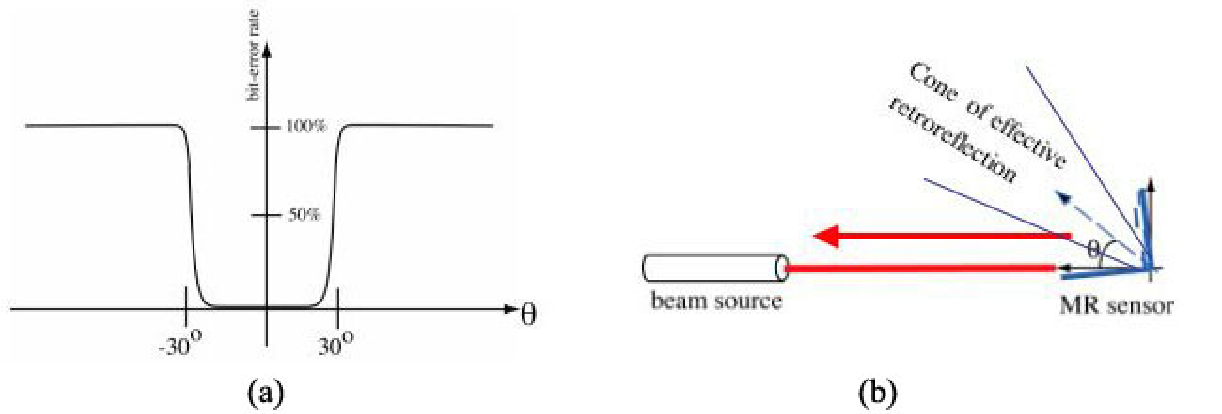

Figure 7: Error-detecting codes and real-time assessment of bit-error rates will be used to steer the modulated retroreflector sensor (MR sensor) to bring it into optimal alignment with the beam source (the case $\theta = 0$ in (b)). In the planar setting depicted here, with ideal optics, the retroreflector would return beams from anywhere within a ninety degree cone, but the practical range of operation is around $\pm 30°$, with the bit-error rate depending on sensor orientation roughly as depicted in (a).

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6. PARTICIPATING PERSONNEL

Co-Principal Investigator:
Prof. John Baillieul :
Department of Aerospace and,
Mechanical Engineering
Boston University
110 Cummington Street
Boston, MA 02215
Phone: (617) 353-9848
E-mail: johnb@bu.edu

Co-Principal Investigator
Prof. Thomas G. Bifano
Department of Manufacturing Engineering
Boston University
15 St. Mary's St.
Boston, MA 02215
Phone: (617) 353-5619
E-mail: tgb@bu.edu

Graduate Student:

Ms Wen Lu
Department of Aerospace/Mechanical Ennginneering
Boston University
110 Cummington Street
Boston, MA 02215